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THE AERODYNAMIC ROUGHNESS OF THE COMPLEX TERRAIN OF WHITE SANDS MISSILE RANGE, NEW MEXICO

By
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ATMOSPHERIC SCIENCES LABORATORY
WHITE SANDS MISSILE RANGE, NEW MEXICO

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WHITE SANDS MISSILE RANGE
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ABSTRACT

The aerodynamic roughness of the extremely complex terrain at White Sands Missile Range has been examined through the analyses of wind and temperature profiles measured on the 62-meter meteorological research tower. The roughness length z_0 was considered as a function of the season and the direction of the mean flow. There was an apparent correlation between the roughness length and the growing season with variations in z_0 from approximately 10 cm in January to 22.5 cm in July. Variations of nearly 60 cm were noted when z_0 was considered on a directional basis.

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INTRODUCTION

The determination of the aerodynamic roughness of the surface in the immediate vicinity of a data collection site is a basic requirement of any study pertaining to the turbulent characteristics of the planetary boundary layer. An aerodynamically rough surface may be defined as one on which the irregularities are large enough to prevent the formation of a laminar sublayer so that the mean flow is effectively turbulent down to the surface (Schlichting, 1960). If the surface is homogeneous with a random distribution of roughness elements, the roughness length may be determined from surface drag measurements, observed neutral profiles, or thermally stratified data and application of diabatic surface boundary layer hypotheses. The roughness length is an indicator of the effective aerodynamic roughness of a surface defined as the height where the velocity profile extrapolates to zero. Unfortunately, a homogeneous surface that allows the development of equilibrium flow from all directions and during all seasons is rare; thus the aerodynamic roughness becomes a function of the local terrain and the vegetative canopy, making the roughness length difficult to determine on a representative basis. Experimental data must be carefully analyzed in terms of small-scale local terrain features and in terms of the growing season.

The purpose of this paper is to examine the roughness length of the terrain in the vicinity of the 62-meter meteorological research tower at White Sands Missile Range as a function of season, wind direction, and the vegetative canopy. The terrain in the tower locale is extremely complex and not homogeneous in all directions, but is considered typical for WSMR. Consequently, the mean flow is not in equilibrium with the surface at all times.

SITE DESCRIPTION

The tower is located in an area that consists of small brush-covered hillocks one to three meters high and randomly distributed. Patches of sand, gravel, native vegetation, i.e., bunch grass, pigweed, and Russian thistle (tumbleweeds) are interspersed between hillocks. The brushy portion of the vegetation consists of mesquite, greasewood, and desert willow.

Modifications to the natural terrain such as clearing, leveling, construction of buildings, etc. contribute to the overall heterogeneity of the surroundings since the tower is located in an area of extensive human activity. A portion of the natural terrain west of the tower remained undisturbed and provided a quasi-homogeneous fetch of approximately 4 kilometers from 220 degrees through 350 degrees, during the first data collection period from April 1958 through April 1960. The determination of the roughness length has been restricted to the times when the mean wind was across this 130-degree sector.

Modification to the terrain in this sector occurred during the second data collection period from January 1962 through October 1963. Approximately two acres were cleared and leveled west of the tower site, giving an 85-meter fetch across bare sand to the natural terrain and vegetation. This new roughness discontinuity altered the mean flow turbulent characteristics of the experimental site drastically.

Data collected in the first observational period are representative of equilibrium flow over a quasi-homogeneous surface, whereas those of the second period possess non-homogeneous turbulent characteristics.

THE ROUGHNESS LENGTH

Sutton (1953) states that the roughness length of a surface may be approximated from

$$z_0 = \epsilon / C \quad (1)$$

where z_0 is the roughness length, ϵ the average height of the roughness elements, and C is a constant usually taken as numerically equal to 30 based on the work of Nikuradse (See Sutton, 1953, and Schlichting, 1960).

For conditions of fully rough turbulent flow in the surface boundary layer of the atmosphere in neutral stratification, the differential equation for the velocity profile may be written as

$$\frac{\partial \bar{V}}{\partial z} = \frac{u_*}{kz} \quad (2)$$

where \bar{V} is the mean horizontal velocity, u_* the dynamic friction velocity, k is Karman's constant and z is height. Integration yields

$$\bar{V} = \frac{u_*}{k} \left(\ln \frac{z}{z_0} \right) \quad (3)$$

where z_0 becomes a constant of integration. Over extremely rough surfaces, those covered with high vegetation, i.e., cereal grains or trees, the velocity profile becomes more complex and (3) does not hold. An empirical correction in the form of a zero-plane displacement factor, d , can be introduced in the form

$$\bar{V} = \frac{u_*}{k} \left[\ln \frac{z - d}{z_0} \right] \quad (4)$$

Equation (4) may be stated as (Lemon, 1963)

$$\bar{V}_{z_g} + D = \frac{u_*}{k} \left[\ln \left(\frac{z_g + D}{z_0} \right) \right] \quad (5)$$

where z_g is the geometric mean of the levels of interest and $D = d + g z_0$, the "effectiveness displacement parameter". Equations (3), (4), and (5) may be solved graphically or algebraically for numerical values of D , d , and z_0 if representative neutral wind profiles are available.

If the atmosphere is thermally stratified, equations (2) through (5) no longer provide a valid solution for the wind profile. It has been demonstrated by Monin and Slobodov (1959), Businger (1961), Panofsky (1962) and others, that in diabatic conditions the wind profile can be represented by

$$\bar{V} = \frac{u_*}{k} \left[\ln \frac{z}{z_0} + \psi \left(\frac{z}{L} \right) \right] \quad (6)$$

where $\psi(z/L')$ is a universal function and L' is the Panofsky, Blackadar, and McVehil (1960) gradient length. Equation (6) predicts a straight line if the velocity is plotted as a function of $\ln z - \psi$ with z_0 as the intercept.

The universal function $\psi(z/L')$ is a stability correction factor that has been developed empirically outside the basic structure of the Monin-Obukhov Similarity Theory to compensate for thermal stratification effects on the wind profile. A reasonably good fit to experimental data can be obtained with Equation (6) in the stability range $0.08 > Ri > -0.10$ (at a reference height of 1.5 meters) where Ri is the gradient form of the Richardson number.

Restrictions on the use of Equations (3), (5), and (6) for graphical or algebraic determination of the roughness length for an experimental data site depend on the thermal stratification of the boundary layer, surface homogeneity, or lack of it, stationarity of the mean flow and growth or decline of the vegetive canopy. With these limitations and restrictions in mind, experimental data measured on the 62-meter research tower were used to determine the roughness length of the typical terrain of White Sands Missile Range.

THE AERODYNAMIC ROUGHNESS OF AN EXTREMELY COMPLEX TERRAIN

During the 25-month period from April 1958 to April 1960, 1611 profiles of wind and temperature for the first 62 meters of the planetary boundary layer were collected. The raw data consisted of 10-minute averages from nine levels on the tower observed eight times a day (0100, 0400, 0700, 1000, 1300, 1600, 1900, and 2200 hours MST). Analyses of these data by Carnes (1961), Tourin and Hoidale (1961), and Swanson and Cramer (1965) indicated that a majority of the samples had been observed under conditions that were sufficiently stationary and homogeneous to permit detailed analysis of the data to establish the aerodynamic roughness of the surface.

Owing to the nature of the terrain and the effect of vegetation on the apparent surface roughness, the analysis considered the season and the mean wind direction across the 130-degree sector to compensate for the homogeneous surface. Profiles observed during the afternoon hours were

treated with caution owing to the possibility of induced error (McCready, 1966).

Usable profiles were first classified by stability regime, utilizing the nine regime scheme of Hansen (1966). Richardson numbers for each profile were computed from

$$Ri = \frac{g}{\bar{T}} \frac{\Delta \bar{T} + \Gamma}{(\Delta u)^2 + (\Delta v)^2} z \ln \frac{z_2}{z_1} \quad (7)$$

where g is the acceleration of gravity, \bar{T} the mean temperature in degrees Kelvin, u and v the north-south and east-west components of the mean wind, Γ the adiabatic lapse rate ($=0.0098 \text{ deg km}^{-1}$), and z the geometric mean of the layer $z_2 - z_1$, where the subscripts indicate the level of interest. Only those profiles where the value of Ri was within the limits $0.08 > Ri > -0.4$ at 7.4 meters were used in the analysis, with emphasis on neutral profiles when possible. Graphical solutions to Equations (3), (5), and (6) were fitted to the experimental tower data for observations below approximately 16 meters. Above this level, direction can no longer be considered invariant with height, and the approach to the geostrophic wind enters into the solution. Stability corrections to the diabatic profiles were obtained from Hansen (1966a) and are based on the KEYPS function which is considered the most reliable and simplest to use of the Similarity Theory log-linear profile hypotheses.

Average values of the roughness length for the research tower site by time of year and wind direction are shown in Figures 1 and 2. There is a correlation between seasonal values and the growing season, with minimum z_0 occurring in January and a maximum in July which represents the rainy season for the area. The directional dependence of the roughness length correlates very well with the isoline analysis of the turbulence intensity measurements of Horn and Trawle (1964).

The second observational period of 1962-1963 gave approximately 2000 hours of data that are considered to be non-homogeneous owing to the roughness discontinuity created by the sandy area west of the tower site. Sutton (1953), Priestley (1959), and Lumley and Panofsky (1964) show that the roughness of bare sand should yield a z_0 value on the order of 0.1 cm, while Sellers (1965) indicates z_0 's in the neighborhood of

0.03 to 0.05 cm for a similar soil surface near Tucson, Arizona. Application of graphical profile analysis techniques to selected samples of the 1962-1963 data gave a roughness length of 1.99 cm with a ± 0.79 cm RMS error which is indicative of the heterogeneity of the mean flow across the roughness discontinuity. Using the approach of Philip (1959), Dyer (1963), Rider, Philip, and Bradley (1963), and Panofsky and Townsend (1964) it was found that at 1.5 meters above the surface, the wind profile was less than two percent adjusted to the new surface after traversing the 85-meter fetch. It is clear that the nonequilibrium conditions existing at the plane of measurement resulted in the erroneous 1.99 cm roughness length for the bare sand fetch as compared with the inferred value of 0.1 cm.

DISCUSSION

Panofsky (1963) has demonstrated the effect of disturbing the natural vegetation of an area when the experimental site was mowed during the Great Plains Turbulence Study (See Lettau and Davidson, 1957), changing the roughness length approximately 30 percent. Halstead (1957) has shown that the surface roughness at the O'Neill, Nebraska, site of Project Prairie Grass (See Haugen, 1958, and Barad, 1959) varied from 0.5 to 1.1 cm owing to changes in vegetation and to differences in wind direction across a quasi-homogeneous terrain. These causes and effects exist at the WSNR tower site. The change of surface roughness, as a function of wind direction and season, is directly attributable to the growth and defoliation of the vegetative canopy and a nonuniform terrain.

The current investigation reveals that the terrain in the vicinity of the tower is extremely rough and not homogeneous with wind direction or seasons. The mean of all roughness lengths determined for the site was 17.4 cm. An inspection of Figures 1 and 2 reveals that this is a reasonable value for the annual roughness regime, but could be unrealistic, especially when the directional data are considered. The best fits to experimental data are obtained by use of the directional roughness length values, although the annual regime curve will yield acceptable results within the limit of experimental error (± 10 per cent). For wind directions other than those within the 130-degree sector, it was found that a reasonable estimate for z_0 was approximately 20 cm which gives solutions within ± 20 per cent.

It was noted that a zero plane displacement correction to the experimental data was not necessary even during the periods in which the brushy portion of the vegetation was in full leaf. It appears that the hardy desert bush is flexible to the point that little or no bending occurs even with brisk wind conditions.

The terrain modification, which occurred before the 1962-1963 data collection period, resulted in a roughness discontinuity of about 100-220 to 1, approximately 65 meters west of the tower. An investigation of wind and temperature profiles observed when the mean flow was across the discontinuity (Hansen and Hansen, 1965) showed that "kinking" of the profiles occurred, and a distinct internal momentum boundary formed with an interface approximately 6.5 meters above the surface. This agrees with the hypotheses of Elliott (1958) and Danovskiy and Townsend (1964) that predict the interface to have a height-to-fetch ratio of 1:10.

The abrupt roughness change has little effect on the magnitude of the lateral and longitudinal intensities of turbulence observed at the tower as noted by Hansen (1966) who found few differences in these parameters when they were compared with values of Swanson and Cramer (1965) for the 1958-1960 data. The major contribution of surface discontinuity was the generation of nonequilibrium flow and the internal momentum boundary.

CONCLUSIONS

The aerodynamic roughness of an experimental site may be determined from the analysis of wind and temperature profiles if the mean flow is considered to be stationary and homogeneous across a sufficiently long uniform fetch to insure equilibrium conditions. The growth of vegetation and slight nonuniformities in the surface with respect to wind direction are other considerations. The surface roughness of a sparsely vegetated and extremely uneven terrain can be determined if caution is exercised in the analysis of the profile data.

Modifications to the natural terrain have been shown to affect the aerodynamic characteristics of a surface to the extent that the mean flow is no longer in equilibrium

with the underlying surface. The resultant nonhomogeneous turbulent flow completely negates the use of conventional profile analysis techniques for determining surface roughness and forces the use of estimated values. The results presented in Figures 1 and 2 are considered to be representative of the roughness length in the vicinity of the 62-meter research tower, whereas the estimate of 0.1 cm for the 85-meter bare fetch can be in error.

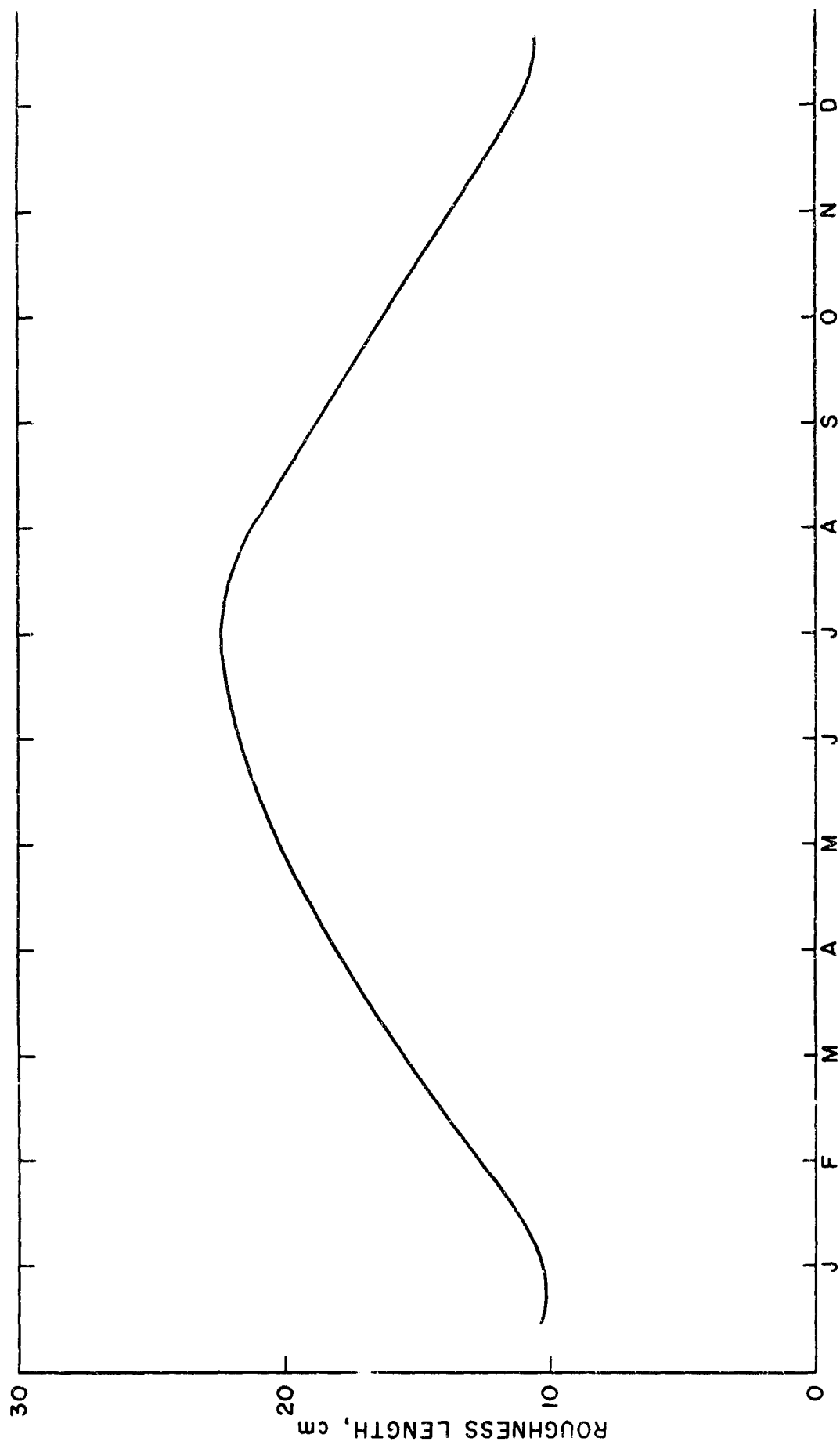


FIGURE 1. THE AVERAGE ROUGHNESS LENGTH BY MONTH FOR WHITE SANDS MISSILE RANGE, NEW MEXICO.

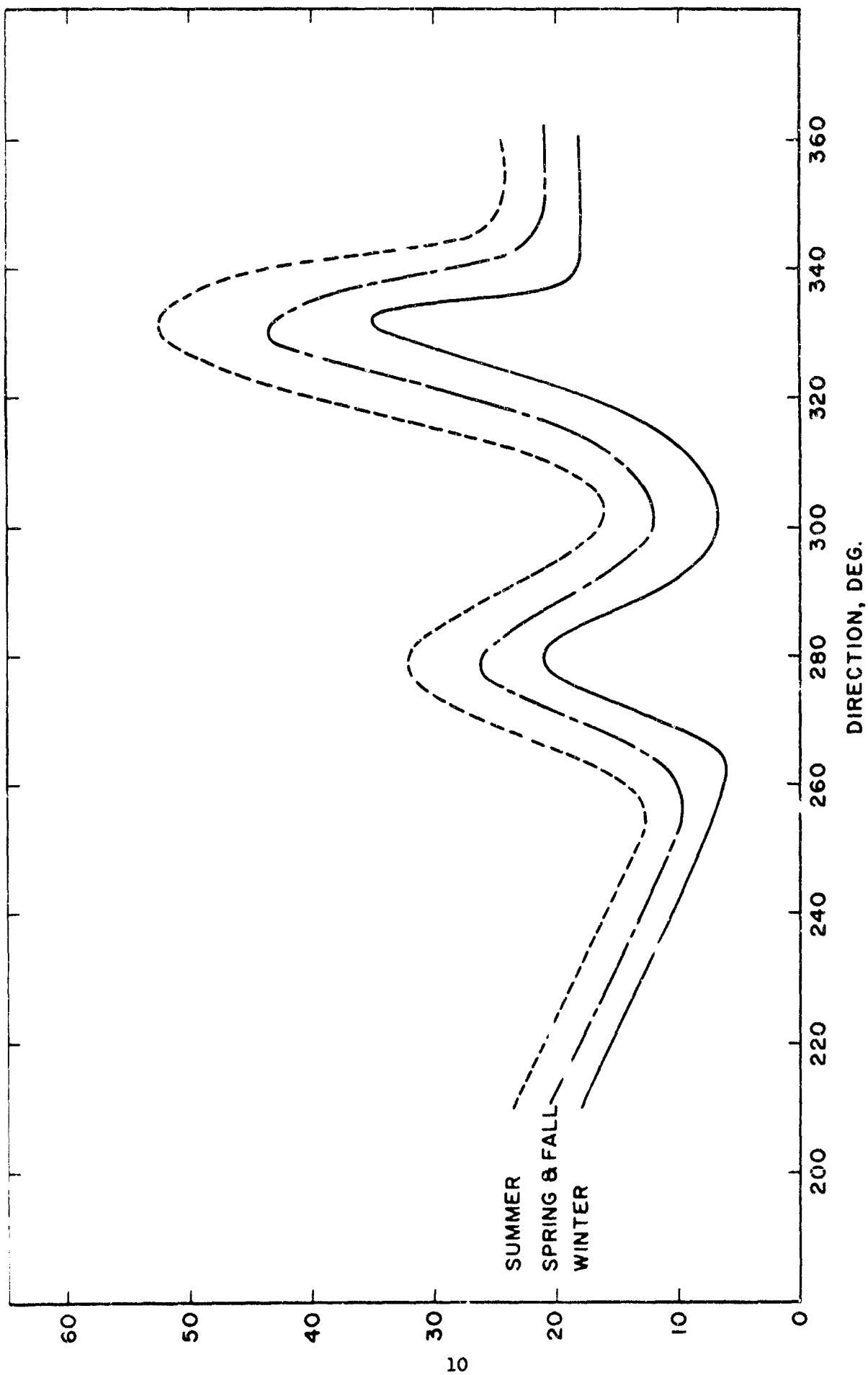


FIGURE 2. THE AVERAGE ROUGHNESS LENGTH BY DIRECTION FOR THE SUMMER, SPRING, FALL AND WINTER SEASONS FOR WHITE SANDS MISSILE RANGE, NEW MEXICO.

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<p>The aerodynamic roughness of the extremely complex terrain at White Sands Missile Range has been examined through the analyses of wind and temperature profiles measured on the 62-meter meteorological research tower. The roughness length z_0 was considered as a function of the season and the direction of the mean flow. There was an apparent correlation between the roughness length and the growing season with variations in z_0 from approximately 10 cm in January to 22.5 cm in July. Variations of nearly 60 cm were noted when z_0 was considered on a directional basis.</p>		

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